Attenuation of Coda Waves in the Source Area of the 1990 July 16 Luzon Earthquake, Philippines

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Abstract

Coda Q values are determined by using small aftershocks of the Luzon earthquake of July 16, 1990 in Philippines ($M=7.8$) recorded by temporary observations. The observations were conducted from August to December in 1990 as a cooperative project between the Disaster Prevention Research Institute, Kyoto University and the Philippine Institute of Volcanology and Seismology. The temporary stations were set at 21 sites, in an area of more than 150km along the Philippine fault and around the city of Baguio. 16–88 events, having S–P time less than 5.0s were analyzed at each station. The single scattering model of coda generation was applied to the band-pass filtered RMS coda amplitudes in five frequency bands from 2 to 32Hz. The time window was taken for all the events from more than twice the arrival time of S wave to 25s from origin time, which indicates that the scattering area contributing to the coda excitation is within a radius of approximately 45km. By fitting the coda Q to the power law, $Q_c=Q_o f^n$, the averaged values of coda Q and frequency exponent n were obtained as $Q_o=68$, and $n=1.06$ around the city of Baguio. On the other hand, $Q_o=165$, and $n=0.84$ in the southern part of the fault where the rupture of the main shock initiated. The lower value of coda Q and the higher value of n in the northern part suggest the existence of large heterogeneities, such as small cracks in the crust made by active aftershock activity around the city of Baguio. As for the southern part of the area, fault movement is considered to be smooth enough not to develop more cracks than in the northern area. The frequency dependence of coda source factors was determined to examine the difference in site amplifications according to respective geological aspects at each observation station. The temporal change in coda Q and coda source factors during four months after the occurrence of the main shock were not obvious when considering their errors.

1. Introduction

Coda parts of S waves are considered to consist of S waves scattered by many heterogeneities distributed randomly in the lithosphere[7, 8, 25, 26, 33]. The decay rate of coda amplitude with time shows the attenuation property of the upper lithosphere. The quality factor determined from the decay of coda amplitude with time is called coda Q (Q_c).

Coda Q values have been determined in various regions in the world[4, 5, 6, 9, 10, 17, 20, 23, 27]. Regional differences in Q_c have also been revealed by the studies of n in the formula of $Q=Q_0 f^n$, where f is frequency. The relationship among tectonic features, seismicity and coda Q has also been pointed out by analyzing coda waves. For example, Jin and Aki[14] searched the regional variations in coda Q for the oceanic lithosphere. They found that younger oceanic lithosphere has a higher frequency exponent n value than older one, which is similar to the continents where the active regions have higher n values. Thus coda Q and n values are effective in determining the attenuation characteristics and their relation to tectonics in studied area.

In and around the Philippine Islands, geophysical studies of crustal velocity structure for the Manila Trench and its fore arc basin were carried out by means of multichanned seismic reflection prospecting[11, 18]. Attenuation of earthquake-shaking intensity with epicentral distance in the Philippines was determined from the data of 83 earthquakes[34]. The result was quite similar to that in the San Andreas fault region. On the other hand, Acharya[2, 3] suggested that the attenuation of ground motion in the Philippines is less severe than in the San Andreas area. Since then, no detail analyses of seismic waves have been performed to reveal the structures of velocity and attenuation in Luzon Island. In particular, Q values have never been determined in the Philippines by using small local earthquakes.

On July 16, 1990, a large earthquake with a magnitude of 7.8 occurred in the central part of Luzon Island. The event was a large shallow intra-plate earthquake common along the Philippine Fault, which, in fact, has caused many large historical earthquakes in Luzon Island. The ground ruptures by the earthquake extended about 150km from Gabaldon (GBD) to Digdig (DIG) as shown in **Fig. 1.** The seismic strong motions caused extensive damage along the Philippine Fault and around the city of Baguio. In order to study the distribution of aftershocks in detail, the observations of aftershocks were conducted two times as a cooperative project between the Disaster Prevention Research Institute, Kyoto University (DPRI), and the Philippine Institute of Volcanology and Seismology (PHIVOLCS). Temporary observation stations were set along the earthquake fault and in the vicinity of Baguio City. Many aftershocks were recorded and about 200 hypocenters were determined accurately by Ohkura *et al.*[21]. Many records of the aftershocks have sufficient excitation of coda waves to determine coda Q.

Seismograms of these temporary observations were used for the determination of coda Q in the crust and upper mantle. The records at 13 observation stations were used for the analyses of coda waves. The regional difference in coda Q values in the aftershock area of the Philippine earthquake is discussed in relation to the aftershock activities. Coda source factors were also determined from the data. Under the assumption that the averaged value of coda source factors of many events at a station indicates the site effect near the station, the frequency dependence of coda source factors for all the observation stations are studied to reveal the relationship between the frequency dependence of coda source factor and the surface geology. .Furthermore, site amplicication is discussed on the basis of the coda source factor. Temporal change in Q_c is also discussed.

2. Data and Analyses

2.1 Data

Seismic wave forms obtained by the two observations of the aftershocks of the 1990 Philippine earthquake of July 16 were used for the analyses of coda Q in this paper.

The first observation was conducted from Aug. 30 to Sep. 4, 1990. Twelve temporary stations were set along the Philippine Fault and in the vicinity of Baguio City. The Locations of the observation stations are listed in **Table 1(a)** and shown in **Fig. 1** by solid triangles and

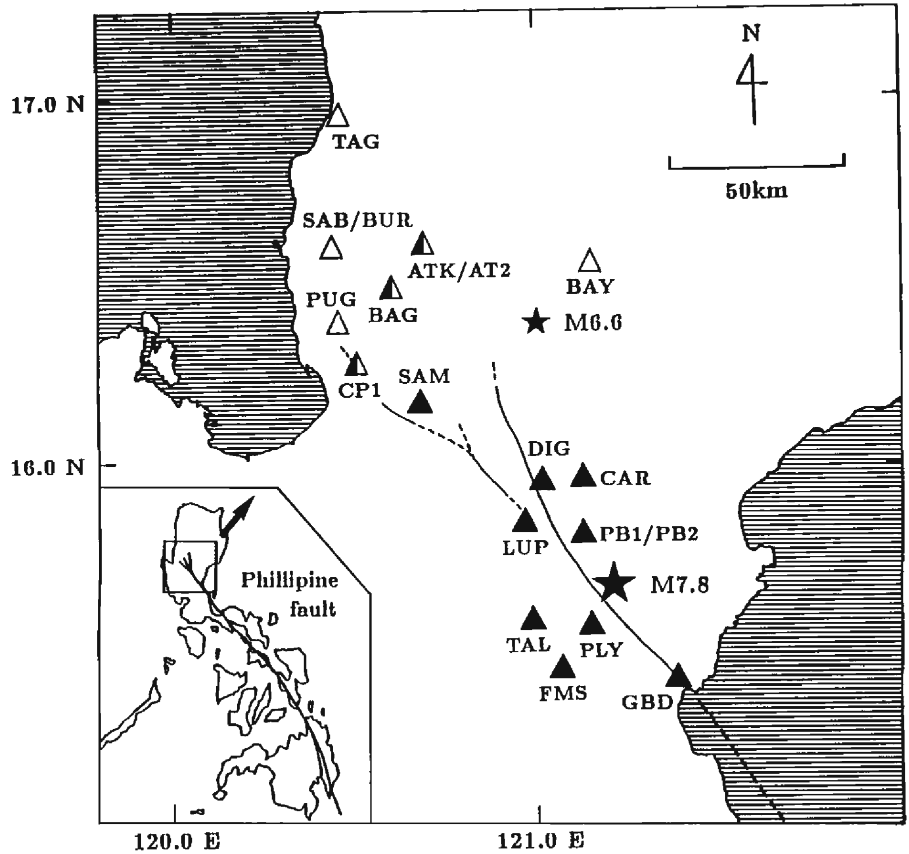

Fig. 1. Map of Luzon Island showing the locations of temporary stations. Solid triangles show the stations set for the first observation. The open triangles show the stations set for the second observation. The half solid triangles show the stations set for both obvervations. Stations SAB, ATK, and PB1 were moved to more adequate neighboring places BUR, AT2 and PB2, respectively, during the observations. The large star shows the epicenter of the 16 July 1990 Luzon earthquake (USGS). The small star shows the epicenter of the largest aftershock. The thick lines show the faults.

half–solid triangles.

The seismograms analyzed were recorded with high–gain vertical–component short period (2Hz) velocity–type seismometers at all stations except the station CAR. A horizontal–component was also set at CAR as the vertical one. Three types of records were used for the analyses. One is digital seismograms recorded in floppy discs at nine stations, another is digital seismograms recorded on audio magnetic tapes at stations GBD and CP1, and the other is FM records at the station CAR. The seismograms at CAR were digitized on a personal computer for the following analyses. Details of the recording systems are described by Ohkura *et al.*[21].

The second observation was conducted from Nov. 17 to Dec. 7 by staff members both of

Table 1. Locations of observation stations; (a) stations of the first observation, (b) stations of DPRI in the second observation, and (c) stations of PHIVOLCS in the second observation. The abbreviation codes correspond to those in Fig. 1.

station	code	lat. (N)	long (E)	Height (km)
(a)				
Palayan	PLY	15.5865	121.1194	0.090
Gabaldon	GBD	15.4501	121.3354	0.125
Talavera	TAL	15.5999	120.9713	0.045
Fort Magsaysay	FMS	15.4363	121.0758	0.100
Pantabangan 1	PB1	15.8143	121.1058	0.150
Pantabangan 2	PB2	15.8110	121.1070	0.220
Lupao	LUP	15.8473	120.9499	0.160
Digdig	DIG	15.9489	121.0007	0.300
Carranglan	CAR	15.9547	121.1055	0.265
San Manuel	SAM	16.1327	120.6862	0.100
Camp One	CP1	16.2353	120.5265	0.120
Baguio	BAG	16.4162	120.6210	1.520
Atok	ATK	16.5058	120.6806	1.824
(b)				
Sablan	SAB	16.4965	120.4867	0.460
Burgos	BUR	16.5183	120.4630	0.460
Atok	ATK	16.5058	120.6806	1.824
Atok2	AT2	16.4983	120.6733	1.750
Pugo	PUG	16.3321	120.4765	0.100
Camp One	CP1	16.2353	120.5265	0.120
(c)				
Tagudin	TAG	16.9180	120.4590	0.100
Bayombong	BAY	16.4830	121.1300	0.320
Baguio	BAG	16.4162	120.6210	1.520

DPRI and PHIVOLCS. In this observation period, four stations (SAB/BUR, ATK/AT2, PUG, BAG) were installed as listed in **Table 1(b)**. In addition, PHIVOLCS operated stations BAG, TAG and BAY from Sep. 30 to Dec. 18 (**Table 1(c)**). In total, seven stations were operated simultaneously for about three weeks. The stations for the second observation were concentrated in the vicinity of Baguio City, in order to reveal the precise distribution of aftershocks in the northwestern end of the aftershock area. The locations of the stations are shown in **Fig. 1** by open and half-solid triangles. Seismometers and recording systems were the same as those used in the first observation. Details of the observation and the method of hypocenter determination are given by Shibutani *et al.*[31].

2.2 Coda Q Analysis

The procedure of waveform analysis is as follows. First, digital waveforms were band-pass-filtered at five central frequencies of 2, 4, 8, 16, 32Hz by using Chebychev's band-pass-filter[24] with a fall-off rate of about 48db/oct. An example of a waveform of raw data and its band-pass filtered traces at station ATK are shown in **Fig. 2**. The maximum and the minimum amplitudes are shown at the top-left of each trace. Next, root-mean-square (RMS)

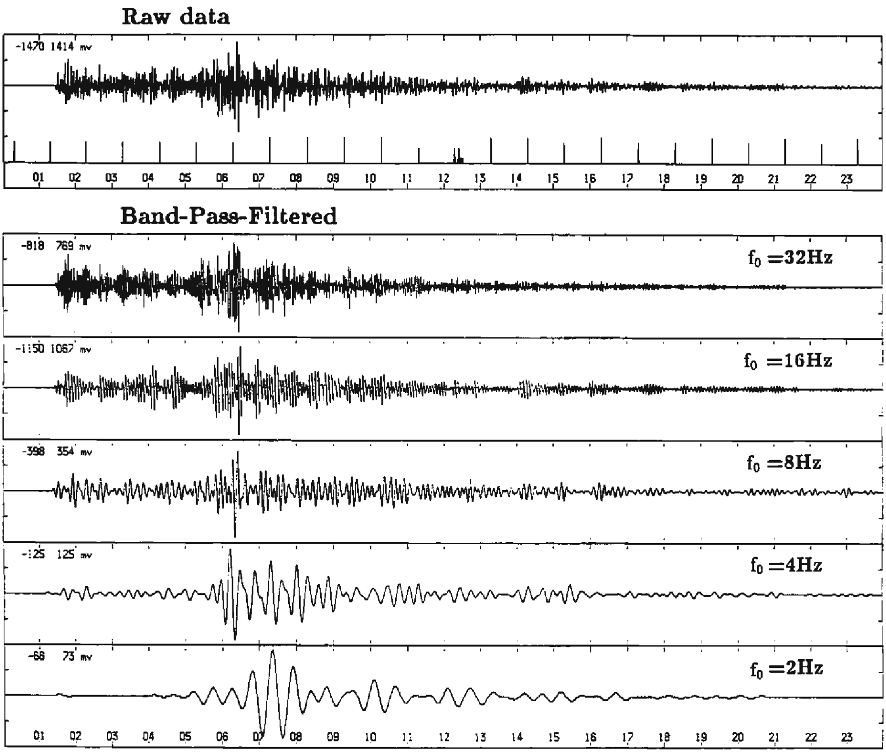

Fig. 2. An example of waveform and time-code signal of JJY at the station ATK/AT2 (*upper traces*). Band-pass filtered outputs using the digital-filter with central frequencies of 2, 4, 8, 16, 32 Hz (*lower traces*). The amplitudes are normalized for each trace.

amplitudes were generated for the filtered outputs in each frequency band, and the amplitudes were moving averaged over a few periods of the waves (1–3s) for each frequency band (**Fig. 3**).

Single scattering model for the generation of coda waves was applied to determine coda Q. When coda waves are assumed to be scattered S body waves, the RMS amplitude of coda wave (A_c) for the central frequency f_0 at the time t after twice the travel time of S waves (t_s) is approximated as,

$$A_c = Ct^{-1} \exp(-\pi f_0 t / Q_c), \qquad (t > 2t_s), \tag{1}$$

where C is the coda source factor, Q_c is the quality factor of coda wave and t is the lapse time measured from the origin time of an earthquake. Coda Q is determined by the least square analyses, applying the formula (1) to the RMS waveform.

Figure 3 shows an example of the coda part of a seismogram to which the formula (1) is fitted. The time window used to determine coda Q is shown in the figure by a pair of arrow heads. The beginning point of the time window is measured from twice the travel time of S

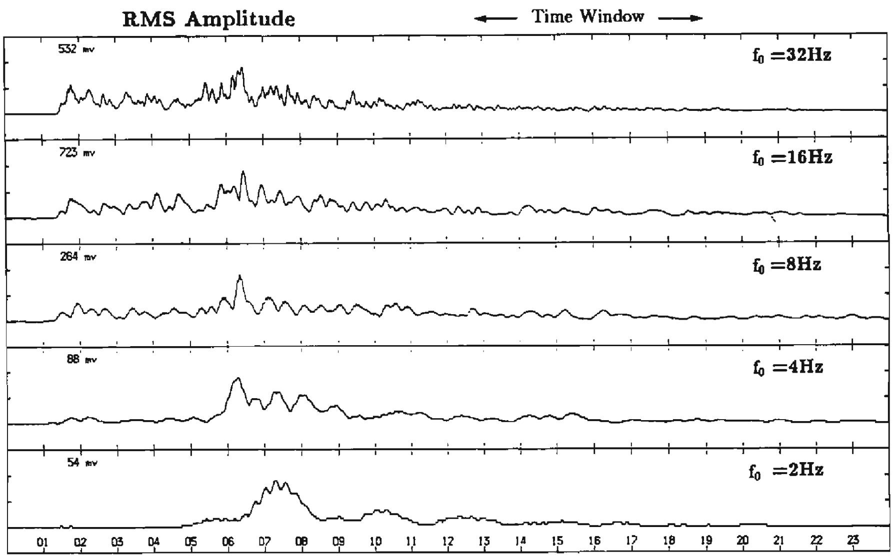

Fig. 3. An example of moving-averaged root-mean-square (RMS) amplitudes of the event shown in Fig. 2 at five frequency bands, 2, 4, 8, 16 and 32 Hz. The time window to which the single scattering model is applied is also indicated by a pair of arrow heads.

wave. Since events near observation stations are necessary to study the regional difference in coda Q, local events with S–P time less than 5s are selected and the beginning of the time window is more than 12s in the present analyses. The end point of the window (lapse time) was fixed at 25s. The S/N ratio of all events was more than two by the end point of coda analyses.

According to the single scattering model, the area contributing to the coda generation is approximated as,

$$r = V_s t/2, \tag{2}$$

where r is the radius of the scattering area, V_s is the velocity of S wave, and t is the lapse time. In this case, we assume that stations were located quite close to the epicenter, so we selected events with S–P times within 5s in the actual analyses. When the lapse time is taken to be 25s and the velocity of S wave is assumed to be 3.5km/s, the scattering area contributing to coda excitation is approximately 45km in radius from formula (2).

Frequency dependence of coda Q in a frequency range higher than 1Hz is roughly given as,

$$Q = Q_0 f^n, \tag{3}$$

where Q_0 is the coda Q value at 1Hz. By studying the difference in the parameter n in the various regions, the characteristics of seismic-wave attenuation in the crust and upper mantle were revealed in relation to tectonic activity[14]. The value n is determined by a least squares method to study the regional difference in n.

3. Regional Difference in Coda Q

The resultant values of coda Q and their standard deviations at five frequency bands for each station in the first aftershock observation are listed in **Table 2.** These values are the averaged ones for all the events at each station. The exponent of frequency n, the averaged value of S–P times and the total number of events used for the analyses at each station are also listed in **Table 2.** The stations are divided into three sets for convenience in **Table 2**; (a) stations in the northern part, (b) stations in the central part and (c) stations in the southern part of the aftershock area.

The obtained values of coda Q and their standard deviations in the second observation are listed in **Table 3.** The stations are also divided into two sets for convenience, (a) stations installed by DPRI, and (b) stations installed by PHIVOLCS.

Since station ATK was moved to AT2, which had quieter surroundings, on Nov. 27 in the course of observation, the values at the two stations and the totally averaged value are also listed in **Table 3.** The averaged coda Q values over the entire observation period at station BAY are listed as well as those divided into three observation periods, (1) from Sep. 30 to Oct. 22, (2) from Oct. 22 to Nov. 13 and (3) from Nov. 13 to Dec. 18. The number of data at BAY is about 300 and enough to examine temporal variations in Q_c, so the averaged Q_c values during the three successive observation periods are calculated as well as that for the entire period. The temporal variations in Q_c are discussed in section 5.

Stations are divided into five sets to show all data clearly and to consider regional variations in coda Q. **Figures 4–1~4–5** show Q_c at (1) stations in the northern part in the

Table 2. The values of Q_c and their standard deviations at five frequency bands for each station in the first observation. The exponent of frequency dependence n, the averaged value of S–P time (s) and the total number of events used in the analyses are also listed for (a) stations in the northern part, (b) stations in the central part and (c) stations in the southern part.

station	code	2Hz	4Hz	8Hz	16Hz	32Hz	n	s–p(s)	N
(a) NORTH									
Baguio	BAG	209±533	761±1839	1284±2309	1932±2720	2764±3777	0.88	3.32	34
San Manuel	SAM	43±65	224±413	776±1261	1170±2243	1605±2645	1.28	3.77	23
Atok	ATK	69±83	451±1286	892±1228	1665±2410	2692±3795	1.25	3.27	25
(b) CENTRAL									
Carranglan	CAR	198±55	344±93	651±256	1471±575	4318±1761	1.10	----	16
Digdig	DIG	74±90	521±1679	431±547	1213±1752	933±1152	0.85	3.06	16
Lupao	LUP	218±621	296±412	1265±1669	1423±1622	2103±2461	0.88	2.62	30
Pantabangan	PB1/2	176±322	166±223	686±1104	1363±1989	2167±3255	1.03	2.89	28
(c) SOUTH									
Palayan	PLY	322±776	777±2032	683±811	1851±2894	1928±2297	0.64	2.88	26
Talavera	TAL	1066±2023	543±684	1404±1750	4087±4811	4598±5513	0.71	3.49	22
Fort Magsaysay	FMS	171±247	508±742	1651±2331	2786±3527	3449±4709	1.11	3.54	25

Table 3. The values of Q_c and their standard deviations at five frequency bands for each station in the second observation. The exponent of frequency dependence n, the averaged value of S–P time (s) and the total number of events used in the analyses are also listed for (a) stations of DPRI and (b) stations of PHIVOLCS. The station ATK/AT2 was moved to a quieter neighboring place on Nov. 27, so the values at the two observation stations and those averaged over the entire data are also listed. For station BAY, averaged Q_c values for the entire data and those divided into three successive periods are listed.

station	code	2Hz	4Hz	8Hz	16Hz	32Hz	n	s–p(s)	N
(a)									
Burgos	BUR	90±130	228±367	487±626	838±1070	1586±2096	1.02	3.33	33
Camp One	CP1	71±94	249±371	507±972	780±912	1730±2209	1.09	3.58	34
Pugo	PUG	77±152	268±395	316±393	1348±1995	2221±3201	1.20	3.15	34
Atok	ATK								
(11/17–11/27)		127±396	275±359	640±924	1514±1952	1929±2694	1.03	2.72	31
Atok2	AT2								
(11/27–12/9)		78±87	310±396	898±1471	1459±1810	1950±2630	1.15	2.01	32
Atok/Atok2 (Total)									
(1st.+2nd. Obs.)		93±234	341±759	808±1198	1537±1997	2146±2949	1.23	2.61	88
(b)									
Tagudin	TAG	76±132	228±360	483±748	972±1658	2072±3288	1.16	4.07	18
Bayombong	BAY								
(9/30–10/22)		53±44	381±694	1083±1720	2219±3044	1895±2891	1.29	2.58	99
(10/22–11/13)		120±220	506±1208	1151±1582	2569±3593	3123±4294	1.17	2.84	97
(11/13–12/18)		68±81	366±591	1288±1909	1921±2741	2505±3724	1.28	3.15	98
Bayombong (total)		80±54	421±844	1172±1688	2199±3035	2485±3591	1.23	2.86	294

first observation (**Table 2a**), (2) stations in the northern part in the second observation (**Table 3a**), (3) stations in the northern part in the second observation (**Table 3a, b**), (4) stations in the central part in the first observation (**Table 2b**), and (5) stations in the southern part in the first observation (**Table 2c**).

Comparing the results of **Figs. 4–1, 4–2** and **4–3**, differences in coda Q are not seen in the northern part of the studied area. Therefore, the regional variation in coda Q is discussed by adding the results of the three datasets. **Figures 4–4** and **4–5** are similar to each other, reflecting the fact that no regional difference in Q was detected between the central and southern parts of the area. The Q values in the two regions were, therefore, added and the difference is discussed in the following.

Resultant frequency dependence of Q_c^{-1} values are shown for the northern and southern parts of studied area in **Fig. 5.** Thick lines in two figures indicate the averaged coda Q values at all stations for each region. Solid circles show the locations of the stations in the northern part, and solid squares and triangles show those in the southern part. **Figure 5** shows that Q_c^{-1} values in the northern part are larger than those in the southern part, particularly in the low frequency range. The averaged values of coda Q and frequency exponent n from the power law in the formula (3) are $Q_o=68$, $n=1.06$ in the northern part, and $Q_o=165$, $n=0.84$ in the southern part, respectively. Epicentral distribution determined by the first observation[21] is

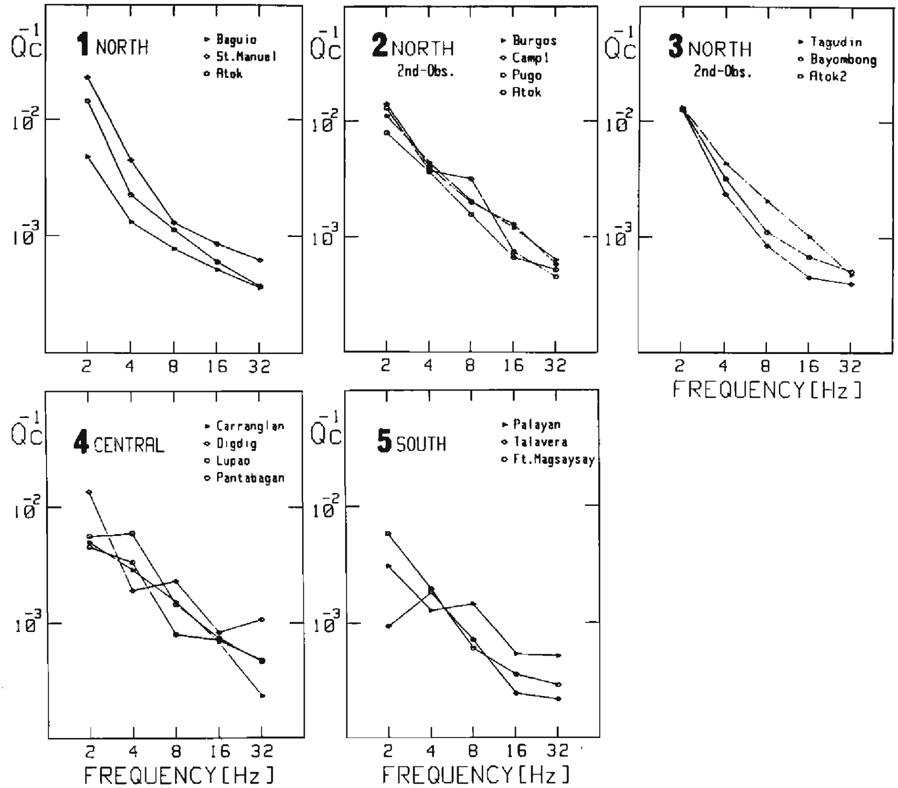

Fig. 4. Frequency dependence of Q_c^{-1}. Each line shows the averaged values at each station. (1) stations in the northern part in the first observation, (2) stations in the northern part in the second observation, (3) stations in the northern part in the second observation, (4) stations in the central part in the first observation and (5) stations in the southern part in the first observation.

also indicated for comparison with the aftershock activity.

Figure 6 shows aftershock distribution determined by PHIVOLCS from the occurrence of the main shock as of Nov. 29, 1990. This figure shows that more aftershocks occurred in the northern part of the aftershock area than in the southern part. This is also supported by the aftershock distribution reported by USGS[19].

Lower values of coda Q in the northern part suggest that the attenuation is stronger due to many heterogeneities, such as small cracks developed throughout a wide area of the crust during the main shock. This corresponds to the high values of n and to the high seismicity around the city of Baguio even a few months after the main shock. As for the southern part, the movement of the fault was so smooth with the ruptures certainly being limited to such a narrow area along the fault that cracks did not form extensively in either number or area compared to the northern part. Similar results of the fault movements during the main shock were obtained from the analyses of long period seismic waves by Abe[1].

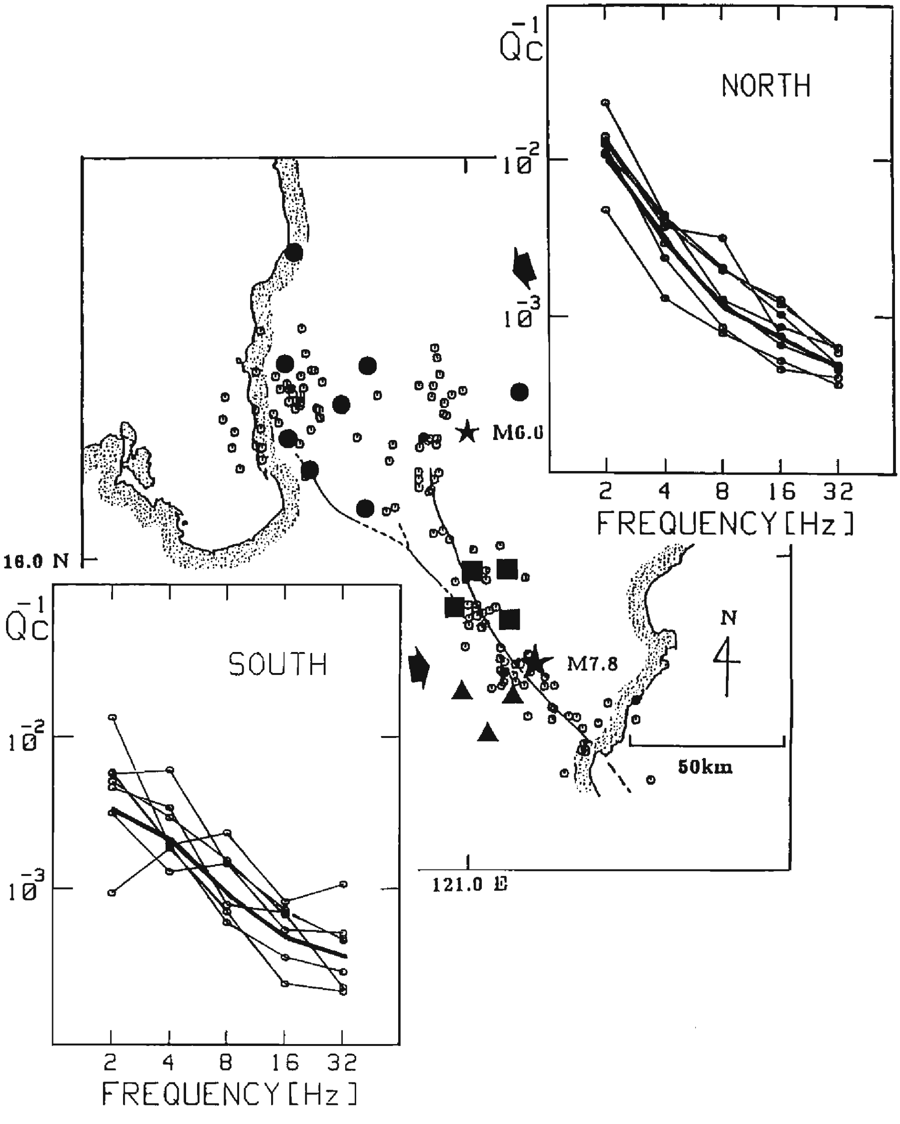

Fig. 5. Frequency dependence of Q_c^{-1} in the northern and southern parts of the aftershock area. Data in Figs. 4–1 to 4–3 are added and shown in the figure of the northern part. While the figure for the southern part consists of data in Figs. 4–4 and 4–5. Thick lines show the averaged values for the northern and southern parts. Solid circles show the location of the stations in the northern part and solid squares and triangles show those in the southern part. Epicenters were determined by the two temporary observations (after Ohkura *et al*[21]., and Shibutani *et al.*[31]). Large and small stars show the main shock and the largest aftershock (USGS), respectively.

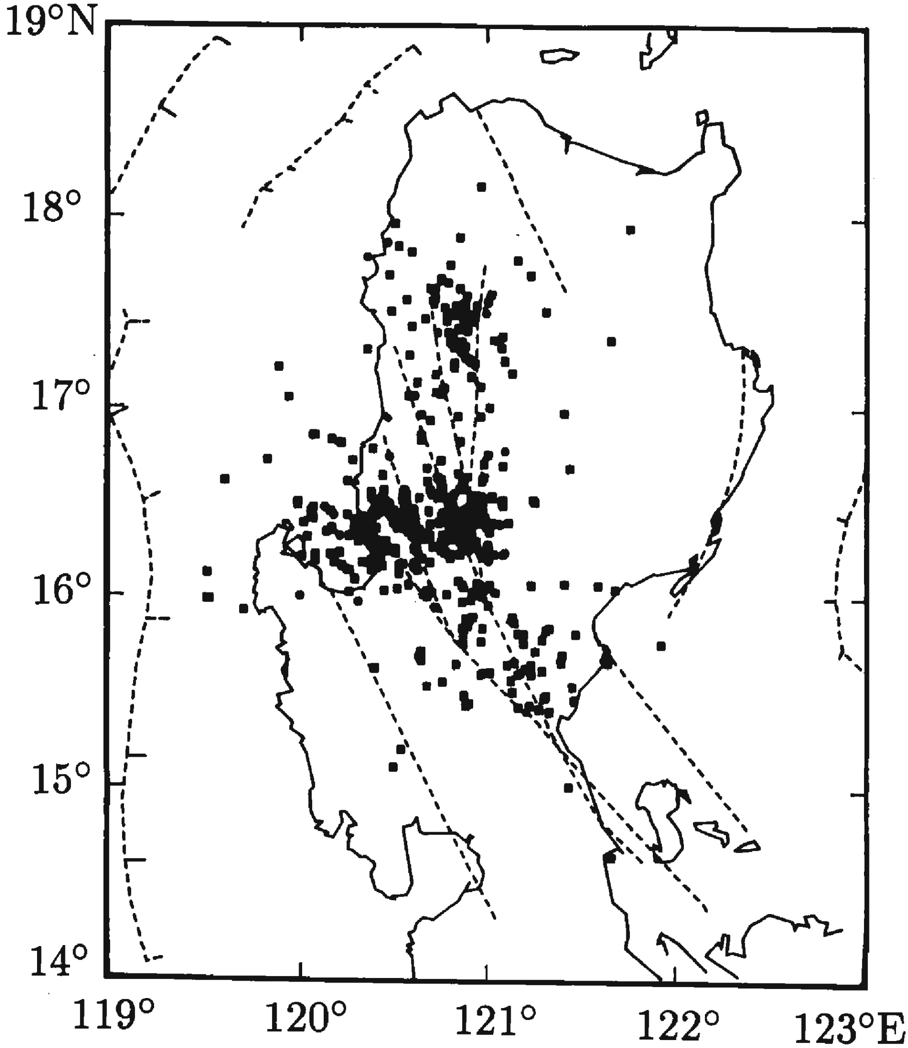

Fig. 6. Aftershock distribution for the 1990 July 16 Luzon earthquake as of Nov. 29. Epicenters were determined by PHIVOLCS.

4. Source factor of Coda

In this section, we discuss the coda source factor (C) in the formula (1). The value of C can be calculated simultaneously with the determination of coda Q for an event at a station. The coda source factor indicates the amplitude at the origin time extrapolated from coda part of seismograms. C is considered to include the effects of radiation pattern, propagation path, and site amplification at an observation station. Aki and Chouet[8] showed the differences in

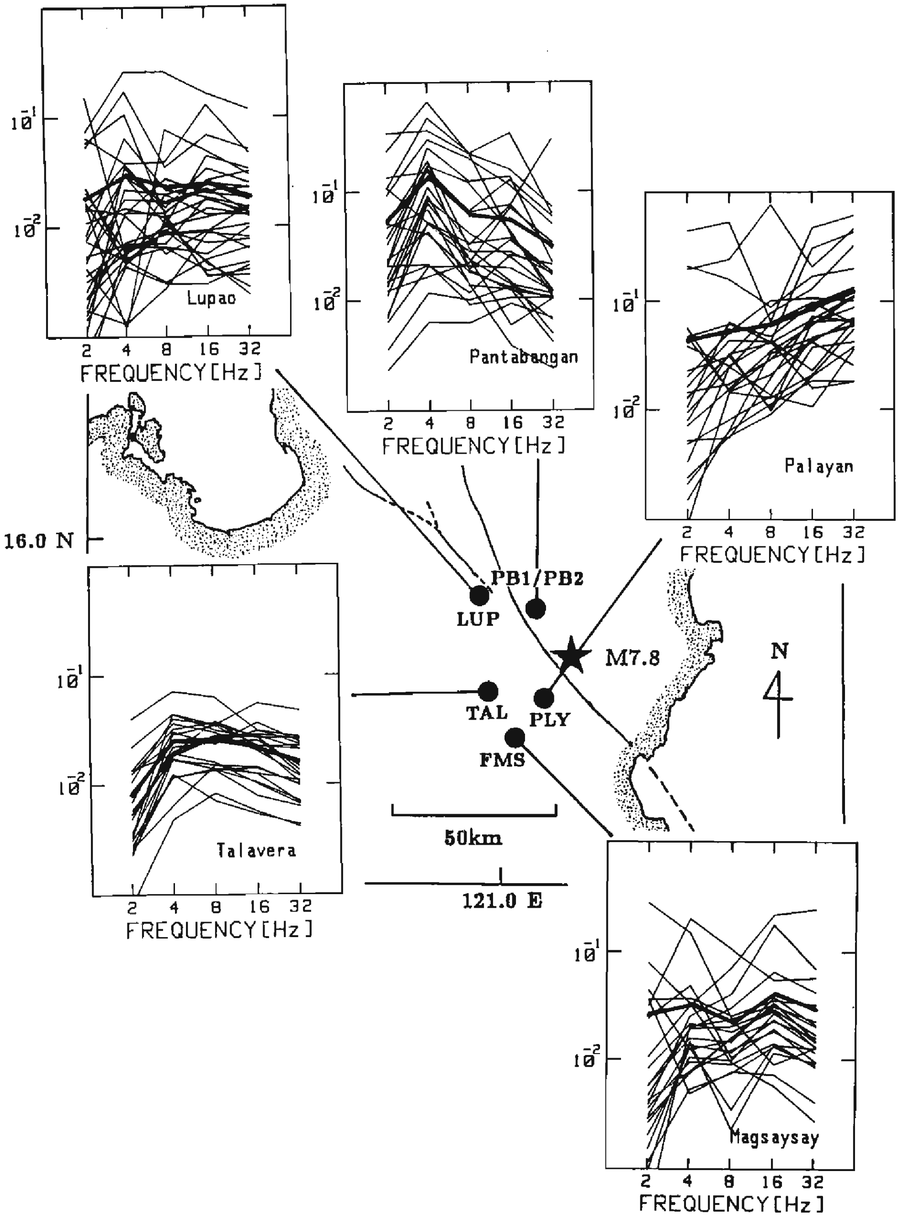

Fig. 7. Frequency dependence of coda source factors at five stations in the southern part. Solid circles are the station locations and the star shows the main shock (USGS). The results of all events are drawn for each station. Thick lines show the averaged values at each station.

frequency response of the coda source factor between California and Japan. Iwata and Irikura[13] tried to separate site effects from source and path effects of S waves. Phillips and Aki[22] tried to separate the source and site effects from coda level in California.

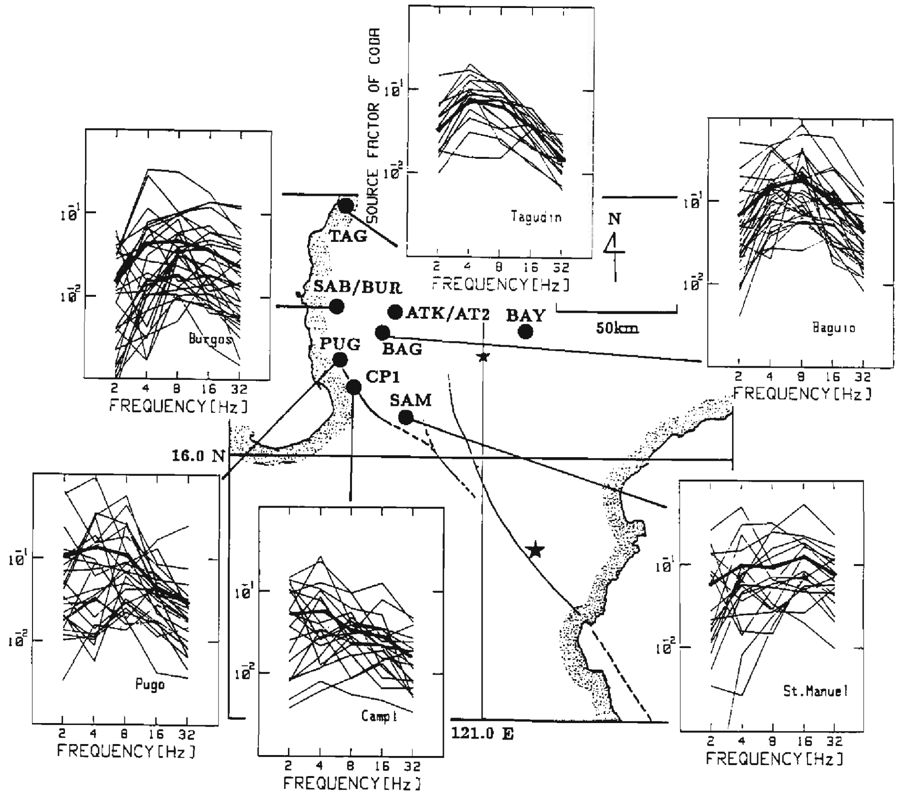

Fig. 8. Frequency dependence of coda source factors at six stations in the northern part. Solid circles show station locations and the large and small stars show the main shock and the largest aftershock (USGS), respectively. The results of all events are drawn at each station. Thick lines show the average values at each station.

We calculated the frequency dependence of the coda source factors for all the observation stations, then tried to reveal the relationship between the frequency dependence of source factors and surface geology near the stations. In the present anaylyses, the path effect of the medium is assumed to be eliminated by fitting a single scattering model of coda generation. The effect of radiation pattern is assumed to be eliminated by averaging many events from various directions.

Figure 7 shows the frequency dependence of coda source factors at five stations in the southern part. The locations of the stations are shown by solid circles in the map. The results at each station for all events are drawn in the figures. **Figure 8** shows the frequency dependence of coda source factors at six stations in the northern area. The results at stations ATK/AT2 and BAY are shown in **Fig. 9** for three different periods of observation. Since many events were recorded at these stations, any temporal change in coda source factor could be examined as well as that in Q_c. However, no clear change was seen in the figures. This is discussed in section 5. Thick solid lines in the figures of the coda source factors (**Figs. 7, 8, 9**)

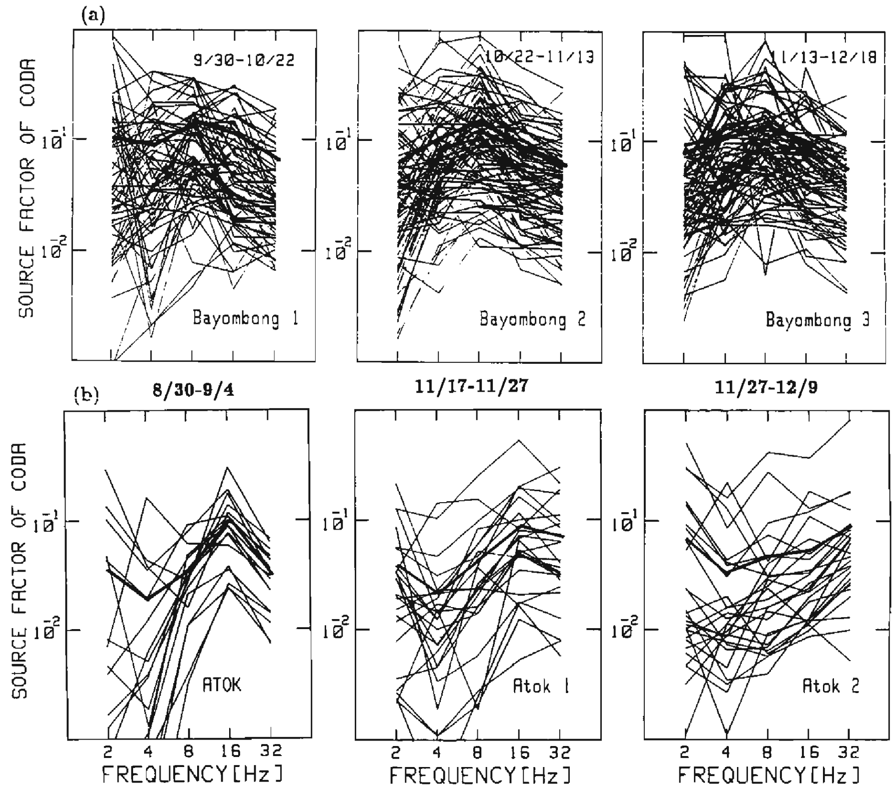

Fig. 9. (a) Coda source factor during three successive periods at the station BAY, from Sep. 30 to Oct. 22 (*left hand side*), from Oct. 22 to Nov. 13 (*middle figure*) and from Nov. 13 to Dec. 18 (*right hand side*). (b) Same at the station ATK/AT2, from Aug. 30 to Sep. 4 (*left hand side*), from Nov. 17 to Nov. 27 (*middle figure*) and from Nov. 27 to Dec. 9 (*right hand side*). Thick lines are the averaged values for each period.

are the average values at each station.

Most of the curves at each station show similar variation with frequency, regardless of their amplitude, so the averaged lines can be compared with each other to discuss their difference. There seem to be clear differences between the frequency responses at the stations. Coda source factor at PB1/PB2 seems to have a peak at 4Hz, while that at PLY is positively proportional to the frequency of 2–32Hz (**Fig. 7**). Those at TAL, FMS and LUP seem to be flat in the frequency range of 4–32Hz. BAG has a peak at 8Hz, SAB/BUR, SAM and BAY have rather flat response to frequency and PUG, CP1 and TAG have high values in the low frequency range (**Figs. 8, 9**).

Phillips and Aki[22] pointed out that the frequency response of site effect is related to surface geology at the stations. They mentioned that 'granite' station has high amplification at high frequency range, 'fault zone' station has high amplification at low frequency range and 'sediments' station has the flat response to frequency. The responses at the stations PB1/PB2, PUG, CP1, and TAG seem to be similar to that of 'fault zone' station (**Figs. 7, 8**). The

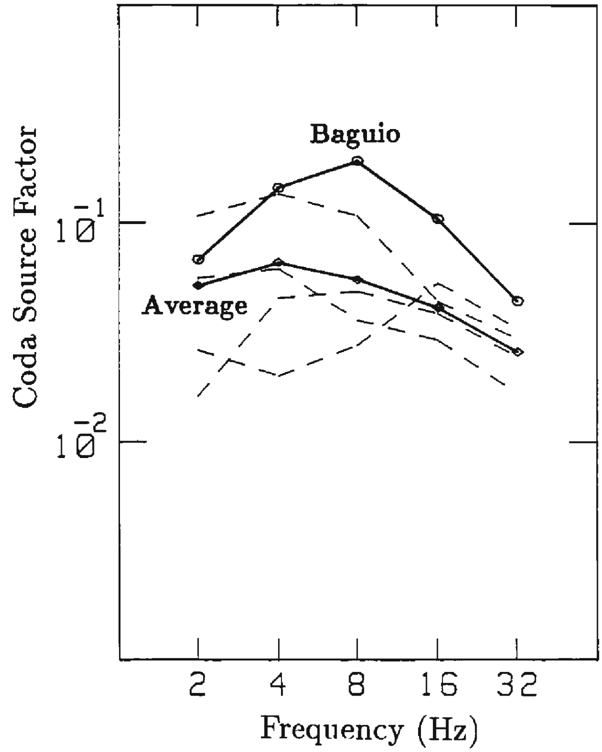

Fig. 10. Frequency dependence of coda source factor at the station BAG (*thick line with cirles*), at other four stations in the northern part (*dashed lines*) and the average of the four stations (*thick line with diamonds*).

frequency responses at PLY and ATK/AT2, have the same type as 'granite' station (**Figs. 7, 9**). At the stations TAL, FMS, LUP, SAB/BUR, SAM, BAY the frequency responses are similar to 'sediments'.

The geological map of the Philippines (after Bureau of Mines, Manila 1963) in the paper by Hirano *et al.*[12] roughly supports the above mentioned relation between the frequency response of coda source factor and geology near observation stations. However, the frequency response at station BAG seems to be exceptional to this classification. The response at BAG is rather flat with a peak at 8Hz (**Fig. 8**).

When the source effects are assumed to be canceled by averaging many events, site amplicication can be detected from the coda source factors. As described above, there seems to be relationship between frequency response of coda source factor and surface geology, so the coda source factor can be related to the site effect. However, when we compare the amplitudes of coda source factors at different stations, magnitudes of the events should be considered. The magnitudes of events at all the stations are almost in the same range, since the stations are distributed over a small area such as the vicinity of Baguio City. In addition, events of the same size were selected.

Thus, we can now compare the absolute values of the coda source factors at five stations in the vicinity of the city of Baguio. **Figure 10** shows the frequency dependence of coda source factors at the station BAG (*thick line with circles*), those at other four stations SAB/BUR, PUG, CP1 and ATK/AT2 (*dashed lines*). The thick line with diamonds represents the averaged value of the four stations. BAG has larger values of coda source factors than the average values of the other four stations, three times at 8Hz, and more than two times in the other frequency ranges. This suggests that larger amplification is caused by site effect at station BAG than at the other stations. This may be one of the possible factors that caused the severe damage of buildings in the city of Baguio.

5. Discussion

The averaged value of Q_0 and frequency exponent n for all the stations in the areas studied are 115 and 0.92 and the averaged value of coda Q at 8Hz is 841. The coda Q value is smaller than that in the southwestern part of Japan, being about 445 at 8Hz in the same lapse time of 25s[17], while the value of the frequency exponent n is 0.88 in southwestern Japan. Therefore, values n are almost the same in both areas, but the intensity of attenuation seems to be weaker in Luzon Island than in the inner zone of southwestern Japan.

The temporal variations in coda duration, or that of coda attenuation involving the occurrences of large earthquakes have been reported by many authors in the various regions[15, 16, 28, 29, 32]. Coda Q values increased after the main shock in some cases. On the other hand, the values decreased or there were no evident changes in coda Q[30] in other cases. Furthermore, if coda Q changes with time, it is very difficult to detect the regional variations in coda Q. In the present analyses, however, unfortunately there are no digital seismic wave data before the occurrence of the main shock, so only the change after the main shock could be examined. The data at BAY could be analyzed to examine temporal changes since many events of about 300 could be recorded with a digital recorder from Sep. 30 to Dec. 18. **Figure 11** shows the temporal changes of Q_c^{-1} at station BAY at five frequency bands. The solid lines are the running averaged values of Q_c^{-1} over 10 days. The main shock which occurred on July 16 is shown by an arrow. The change in averaged Q_c^{-1} is small, but it is not certain whether it is due to error or not. Thus, the temporal change in averaged coda Q is not clear for the observation period of about 80 days, considering the deviations.

Site amplification of S waves is important, because most of the severe damage is caused by direct S waves. Therefore, it is necessary to examine the relation between site amplification of S waves and that of coda waves. **Figure 12** shows the frequency dependence of the maximum amplitudes of S waves (*upper figures*), coda source factors (*middle figures*), and their ratios (*lower figures*). The stations are BAG (*left hand side*) and SAB/BUR (*right hand side*). The ratios of maximum amplitudes of S wave to source factors of coda are roughly constant at both stations, BAG and SAB/BUR in the frequency range of 4–32Hz. This indicates that the frequency dependence of direct S waves and coda waves has almost the same ground response. Therefore, the site amplification determined from coda waves seems to have characteristics similar to that of S waves.

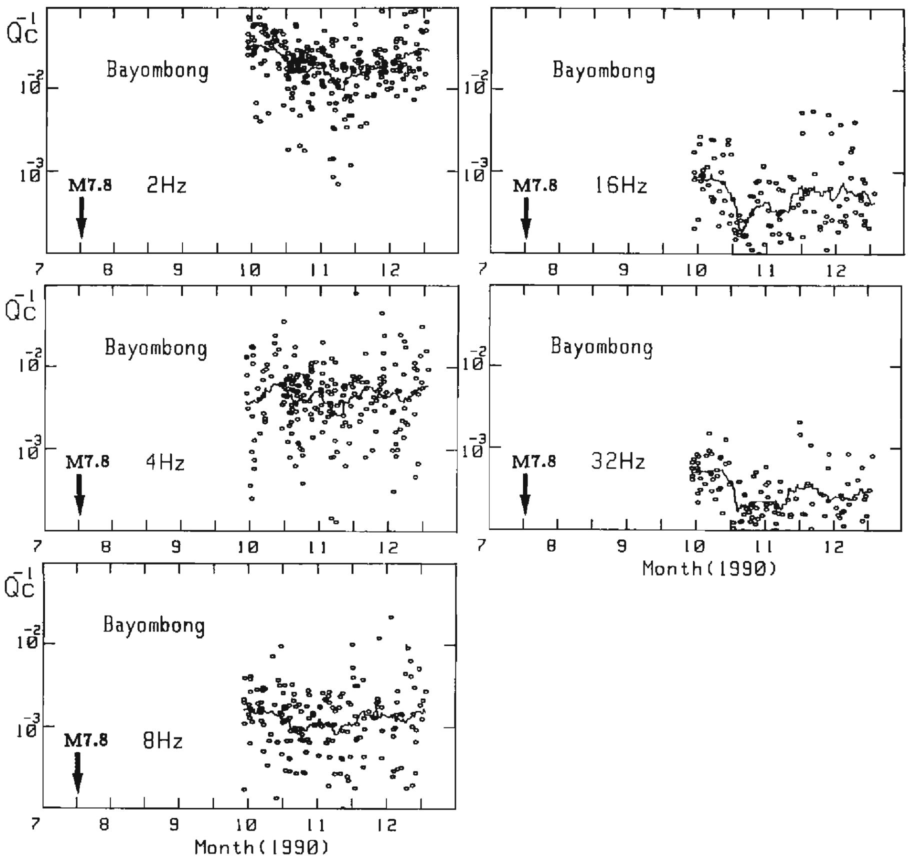

Fig. 11. Temporal change in Q_c^{-1} at station BAY at five frequency bands. The observation period was from sep. 30 to Dec. 18. The solid lines are the running averaged values of Q_c^{-1} over 10 days. The main shock which occurred on July 16 is shown by an arrow head.

6. Conclusion

Coda Q and coda source factor were determined along the Philippine Fault zone in Luzon, using the data of aftershocks of the 1990 July 16 Philippine earthquake recorded at 15 temporary stations. The results of our analyses are as follows :

1. Coda$Q$ were determined for 15 observation stations by applying the single scattering model of coda wave generation. When the frequency dependence of coda Q is represented by the formula $Q=Q_0f^n$ in the frequency range from 2 to 32Hz, the average value of Q_0 and frequency exponent n is $Q_0=115$, $n=0.92$, respectively. The Q value is larger than that in the southwestern part of Japan in the same lapse time of 25s.
2. Coda Q is rather small in the northern part along the Philippine Fault than in the

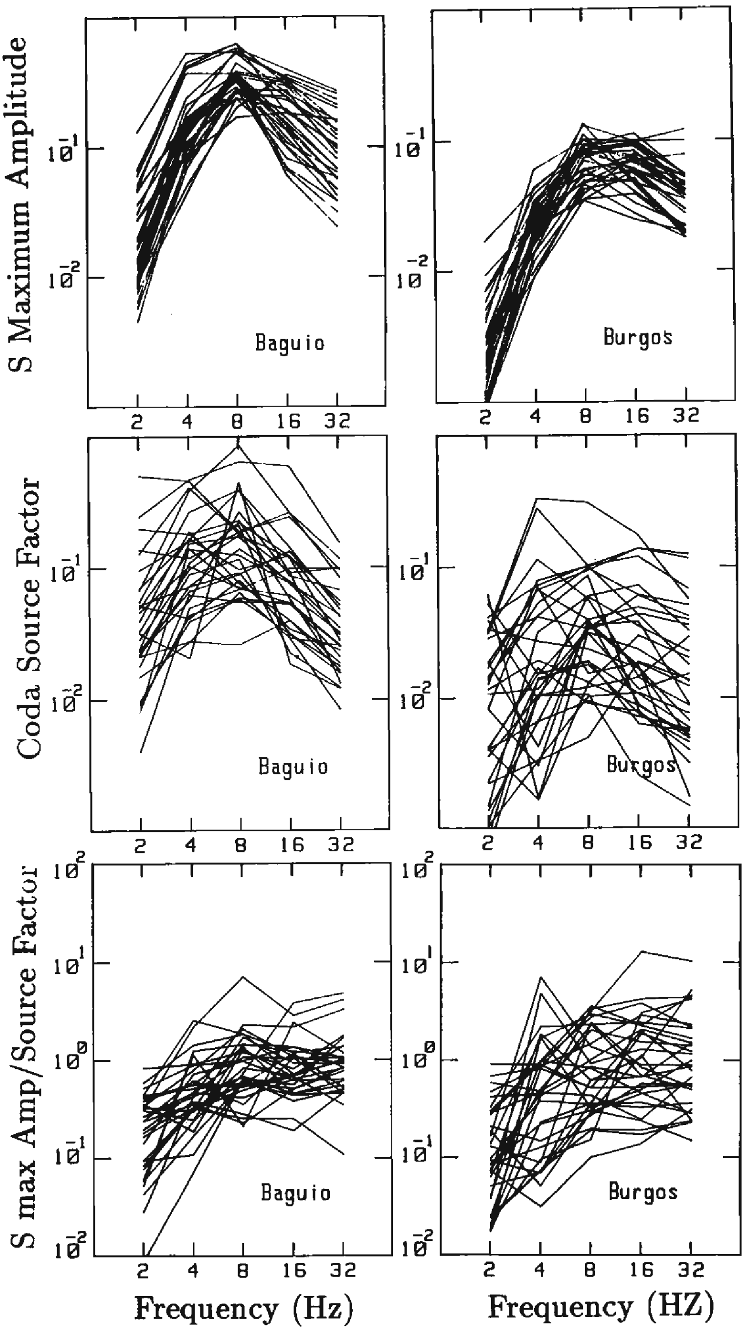

Fig. 12. Frequency dependence of the maximum amplitude of S wave (*upper figures*), coda source factor (*middle figures*) and their ratio (*lower figures*) at stations BAG (*left hand side*) and BUR (*right hand side*).

southern part. The differences in Q_c seem to be related to the aftershock activity, which is more active in the northern part around the city of Baguio than in the southern part near the starting point of the main shock.

3. Coda source factors were determined for all the events at every station. These factors include source, path and site effects. The frequency dependence of the coda source factor seems to involve the surface geology at observation stations with the coda source factor seemingly sensitive to site amplicication.
4. The temporal changes in coda Q and coda source factor during the observation periods are not evident in these analyses because of the short period of observations of only about three months.

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